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METHODS OF EVALUATING PULSED VIBRATIONS (VIBRATION EVALUATION METHODS 3)

T. Miwa, Y. Yonekawa

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METHODS OF EVALUATING PULSED VIBRATIONS

(VIBRATION EVALUATION METHODS 3)

Miwa, T., Yonekawa, Y. *

ABSTRACT. Pulsed vibrations seen in forging and pile driving works have almost occupied the vibration problems concerning human sensation. Results derived by Reiher & Meister as shown in Figure 1 are helpful for assessment of the pulsed vibrations. However, they have treated damped vibrations alone, although there are several other kinds of pulsed vibrations such as pulsed sinusoidal and built-up vibrations (Figure 2). /33**

Sensation of the pulsed sinusoidal (PS) vibration of a certain constant level was matched to continuous (CS) vibration of variable level having the same frequency as the fundamental frequency of the PS vibration. Duration of PS vibration was changed between 6 and 0.007 sec. The results of the matching experiments on the whole body and the hand for vertical or horizontal vibration are shown in Figures 3 a, b and c. The ordinate indicates VAL_p — VAL_j (dB) and the abscissa the duration of the PS vibrations (t) (sec). VAL_p means vibration acceleration level (VAL) of the CS wave which has the same maximum amplitude and the same fundamental frequency as the PS vibration, and VAL_j means the VAL value of the CS vibration judged as the equal sensation with the PS vibration. These results are approximated by three lines formulated as,

$VAL_p - VAL_j = 7 \log_{10} T_o/t$, where T_o is the critical time limit which was nearly 2 sec for 2—60 Hz, 0.8 sec for 60—200 Hz and 0.5 sec above 200 Hz.

Then, the sensation of the damped or the built-up vibration was equalized to that of the PS vibration having the same fundamental frequency and the maximum p-p amplitude by changing the duration of the PS vibration every half period of its fundamental frequency. It was found that the damped vibration, regardless of decay processes, is equalized to one period of the PS vibration and that the built-up vibration is equalized to the PS vibration of the duration which corresponds to its duration just when the amplitude of the built-up vibration is smaller by 1.5 dB from its maximum value. The matched

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** Numbers in the margin indicate pagination in the foreign text.

duration of the PS vibration is defined as equivalent duration (Table 1). Thus, the vibration greatness sensation for the damped or the built-up vibration can be estimated from the equivalent PS vibration.

On the other hand, the estimated values were compared with the observed values which were determined by the sensational comparison between the damped or the built-up vibration and the CS vibration having the same fundamental frequency. Both values are in good agreement as seen in Table 2. /34

Evaluation methods for these three kinds of pulsed vibrations were eventually established.

1. Foreword

The manner in which the human body responds to pulsed vibration is an interesting psychological question. That is to say this question has value in elucidating the mechanics of vibration sensing.

Moreover, in the labor environment and in the field of public nuisance vibrations, the pulsed vibrations in forging factories and pile driving work-sites are the principal problems. This is because impulsive vibration is sensed easily by the human body. One feels, therefore, the need for a method of evaluating pulsed vibration.

Considering, also, the construction of vibration meters, the dynamic characteristics of the indicator section should be examined from the view-point of human response to pulsed vibrations.

For the above reasons, measurements of the psychological response to pulsed vibration have been anxiously awaited. We made tests of pulsed vibrations related to evaluation methods.

2. Past Experiments

(a) The Mechanics of Sensing

G. von Bekesy [1] measured cutaneous response to impulsive vibrations in the same way that response to impulsive sound is measured. He demonstrated that a duration on the order of 1.2 seconds is required for a "magnitude" sensation to be generated. He further discovered that it takes more than one second for the magnitude of a taste sense or smell to be generated [2]. It was concluded that a determination of the site of a stimulus could be completed in several seconds, but that a longer time was required to determine magnitude.

(b) Impulsive Vibration Evaluation Methods

Few reports have been published on impulsive vibrations and only the data of Reiher-Meister [3] are known. They made a study of emotional responses (perception threshold) (I_a) easy perception (I_b), strong perception (I_c), very unpleasant (II_a) and extremely unpleasant (II_b)) in standing and reclining positions to repeated decreasing vertical vibrations. They represented the correlation between maximum peak, peak (p-p) displacement, and rise time and emotional response (Figure 1).

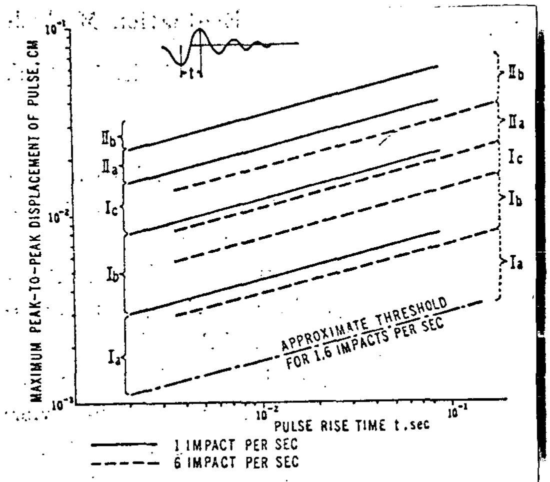

Figure 1. Threshold and emotional response to repetitive damped vibrations in standing or supine posture.

The ordinate denotes the maximum peak-to-peak displacement of damped vibration and the abscissa its rise time. Its repetition rate was changed in two values, namely, one impact per sec (solid line) and six impacts per sec (dotted line). The emotional responses were classified in five grades; theshold of perception (I_a), easy perception (I_b), strong perception (I_c), very unpleasant (II_a) and extremely unpleasant (II_b) (After Reiher and Meister [3]).

When studying actual vibrations, there is not only degenerating pulsed vibrations one must also consider what should be called sinusoidal pulsed vibrations, built-up pulsed vibrations, etc. That is to say the results in Figure 1 alone are insufficient. Moreover, the results of Bekesy cannot be used directly in a vibration evaluation method.

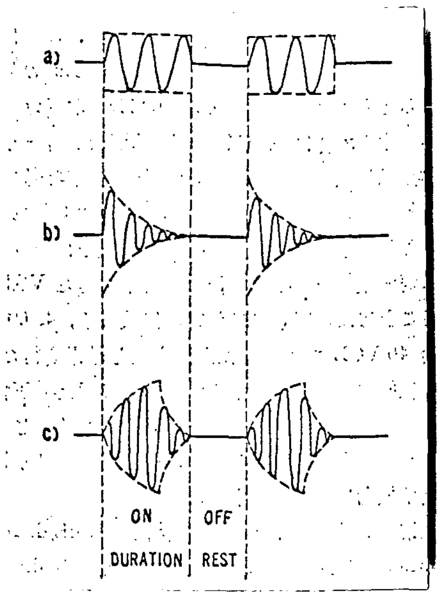

Figure 2. Wave forms of three kinds of impact vibrations: a, pulsed sinusoidal vibration; b, damped vibration; and c, built-up vibration.

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We accordingly considered methods of evaluating the three types of impulsive vibration shown in Figure 2. In this instance, as well, a problem is the apparatus for generating pulsed vibrations. As our power amplifier is of the OPL type, there was no wave-form distortion caused by the output transformer. There was, in addition, little distortion caused by the vibration platform since the resonance frequency of the platform was in the vicinity of 3 Hz. It was possible to accurately regenerate the input wave-form as a vibration acceleration wave-form.

3. Test Methods

(i) Pulse Signal [4]. Pulsed sinusoidal vibration and built-up vibration were constructed by the 100% modulation of a continuous sine wave with short waves and integrated short waves. A L-C tank circuit discharge was used for the damped vibrations. In generating the electrical signal, particular attention was paid to pulse wave-form distortion particularly in the built-up section and the pedestal (the difference between the direct current level in the pulse period and the rest period). As the pedestal is directly sensed by the subject, a gate was made with FET (field effect transistor) in order to prevent this. Additionally, a five column decimal counter was used in order to vary the length of the pulse phase and the resting phase at will. The pulsed sine wave could be generated every half period.

The modulated frequency is called the fundamental frequency.

(ii) Magnitude of Pulsed Sinusoidal Vibration. The method of paired comparison was used to compare pulsed sinusoidal vibration (constant levels) and continuous sinusoidal vibration (variable levels) to determine their equal sensation points. In both of the compared vibrations, it was given that the vibration frequency was the same as the fundamental frequency. In order to facilitate judgment, the pulse period was varied from a long period to a short period (6~0.007 seconds). The tester varied the continuous sinusoidal vibration levels upwards and downwards while the fundamental frequencies for the impulse vibrations were 2, 5, 10, 20, 40, 60, 100, 200 and 300 Hz except that only the hand was tested at 300 Hz. With each pair, vibration was imposed in the order pulsed sinusoidal vibration (repeated twice every other second), continuous sinusoidal vibration (three seconds) and rest (three seconds).

(iii) Subjective Equalization of Damped Vibration and Built-Up Vibration to Pulsed Sinusoidal Vibration. Damped vibration and built-up vibration were compared to pulsed sinusoidal vibration by the method of compared comparison. The fundamental frequency was made the same for both of the compared vibrations. The examiner reduced the pulse period of the pulsed sinusoidal vibration without changing the amplitude until the subject determined the equal sensation point. The tests were made with the maximum p-p value in damped vibration and built-up vibration the same as the p-p value in pulsed sinusoidal vibration. The fundamental frequencies of the damped vibration was 15 and 27 Hz while those of the built-up vibration were 20, 40 and 60 Hz. These levels were selected because they are the most widely encountered frequencies.

In the tests, the wave-form in damped vibration and built-up vibration was changed by changing Q in the L-C circuit and the time constant in the integrating circuit. Each vibration was repeated every other second.

The maximum p-p value for each pulsed vibration was compared with the p-p value of a continuous sine wave having the same frequency on a memory scope to determine the vibration acceleration level (VAL) of the continuous sine wave. The characteristics of each pulsed vibration were described in terms of its VAL value, its pulse period and its fundamental frequency.

The subjects were 10 males who were the same members as those named in the previous report. Measurements were made for whole-body vertical and horizontal vibration in the seated position and for vertical hand vibration. The postures were the same as in the first report.

3. Results

(i) Pulsed Sinusoidal Vibration. The "vibration magnitude" and the results for whole-body vertical and horizontal vibration and for hand vibration are given in Figures 3 a, b and c (average values for the 10 subjects). The ordinate gives the relative values for the magnitude of the vibration as estimated by the subjects. That is a value obtained by subtracting the continuous sine wave VAL value (VAL_j), which was judged to be equal, from the VAL value of a continuous sine wave having a peak value the same as the pulsed sine wave (VAL_p). The abscissa is the pulse period (duration) of the pulsed sinusoidal vibration (seconds). In the figure, the fundamental frequency of the pulsed sine wave is represented by various symbols. Further, the tests /36 were conducted at as close to the same values as the input limitations of the power amplifier would permit in order to make the pulse level show as close to the same effect on the frequency as possible. Figures 6 and 9 in Report No. 1 were used to convert VAL to VGL.

When approximation curves are drawn in Figure 3, three straight lines are produced. The solid line shows the low frequency region of 2~60 Hz. At the frequencies between these limits magnitude generally approximate this line. There are no clear differences as a function of frequency between 2 and 60 Hz. The results between 60 and 200 Hz are represented by the broken lines. Tests of the hand were also made at 300 Hz and the results are approximated by the dashed and dotted lines. It is believed that the reason why the approximation line differs at the high frequencies is that a different vibration receptor is involved. This is not the effect of the pulsed vibration level having a slightly lower VGL value above 100 Hz than at the lower fundamental frequency. The reason for this conclusion is that the same results as in the illustration were obtained in tests at 40 VGL at 4 and 60 Hz.

A special characteristic in the case of pulsed sine wave sound is that the number of repetitions is sensed more strongly in certain pulse period regions than the continuous sine sound [5], [6], [7]. In the case of vibration, however, pulsed vibration is always sensed less than continuous vibration.

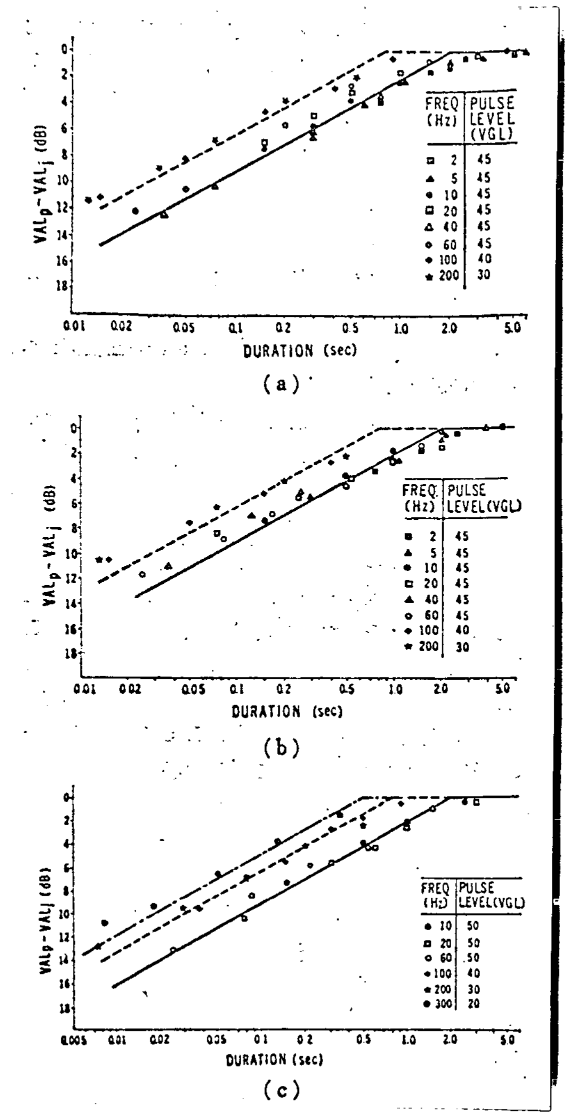

Figure 3. The relation between VAL_p—VAL_j (dB) and the duration (sec) for the pulsed sinusoidal vibrations.

a, on the whole body vertical vibration; b, on the whole body horizontal vibration; and c, on the hand vertical vibration. Each symbol means the average value observed on 10 subjects.

The gradient of the three previously mentioned approximation curves was 7 dB/decade of duration. During our tests there were two subjects who demonstrated a gradient of 10 dB/decade, however the average was 7 dB/decade. In the case of pulsed sinusoidal sound, it has been observed that there are times when a gradient close to about 10 dB/decade appears [8]. The values in Figures 3 a, b and c are the averages of the observed values. A representative example of the standard deviation is shown in Figure 4 for whole-body vertical vibration at 2, 20 and 100 Hz. Deviation increases as the pulse period decreases in length since judgment becomes more difficult. Including the other cases, the maximum standard deviation remained within ±4 dB.

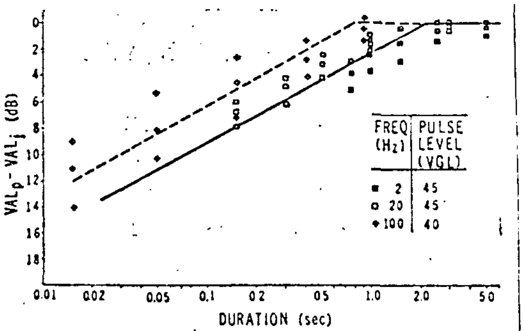

Figure 4.

In Figures 3 a, b and c, the magnitude of the pulsed sinusoidal vibration increases together with increases in the pulse period reaching a maximum value where it becomes saturated. The pulse period where this maximum value is attained varies with the frequency. It is estimated to be 2 seconds at 2~60 Hz, 0.8 seconds at 60~200 Hz and 0.5 seconds above 200 Hz. This value is called the critical time limit. The value is an important quantity in determining the rectification of the vibration meter and its dynamic characteristics, including the indicator section. In noise meters, this value is 200 msec which is called a fast dynamic characteristic [9]. In the case of noise, it is believed to be desirable that this value be between 2 and 0.5 seconds. This also agrees with Bekesy's results for the skin [1]. Further that 7 dB/decade is indicated suggests that the integrating action of vibration sensations is inadequate. /37

The result in Figures 3 a, b and c can be represented as in Eq. (1).

$$VAL_p - VAL_j = a \log_{10} \frac{T_o}{t} \quad (1)$$

Where a — 7 dB/decade of duration; T_o — critical time limit; t — sinusoidal vibration pulse period (duration) seconds.

(ii) Study of Experimental Conditions [4]. The experimental conditions which produced the results indicated above were selected from the following preparatory tests.

Tests were made with the 10 subjects using vertical vibration in a seated position on: (a) the number of pulsed sine wave repeated, (b) the length of rest time between the pulsed sine waves and (c) varying the levels of the pulsed sine waves with pulsed sinusoidal vibration having a fundamental frequency of 20 Hz and a level of 45 VAL_p.

(a) A study was made of the points equivalent to continuous sinusoidal vibration when pulsed sinusoidal vibration was applied once and was applied every other second five times, however there was no clear difference as a function of the number of pulsed vibrations. Accordingly, they were repeated twice.

(b) Equivalent continuous sinusoidal vibration points were studied varying the length of the rest period between 0.5, 1.0, 2.0 and 5.0 seconds with five repeated pulsed vibrations. It was noted that the results were virtually all the same above one second, but that there were some differences at 0.5 seconds. For this reason, it was decided to repeat the pulse twice with a one second rest.

(c) Tests were made at pulsed sinusoidal vibration VAL_p values of 45 and 55. The vibrations felt severe at 55 VAL_p, but curves with the same trends as those in Figure 3 were obtained. For this reason, 45 VAL_p was used. In the case of hand vibration, pulsed sinusoidal vibration was tested with vertical vibration at 20 Hz and 50 VAL_p, but the results were the same as they had been for vertical vibration. Accordingly, horizontal vibration was omitted for the hand.

(iii) Thresholds for Pulsed Sinusoidal Vibration. Using the measurement method described in Report No. 1, threshold values were measured for whole-body vertical and horizontal and hand vertical pulsed sinusoidal vibration. The tests were made at frequencies of 5, 20 and 60 Hz with pulse periods between 0.01 and 2 seconds. That is to say, measurements were made of the increase in threshold values as the pulse period decreased.

As a result, it was found that the standard deviation for the pulsed vibration threshold was quite large having a maximum of ±6 dB. This gradient may be considered as about 7 dB/decade of duration. That is to say, it is in agreement with the gradient of the pulsed vibration magnitude curves in Figures 3 a, b and c. It was also noted that the integral relationship in the threshold values were also inadequate.

(iv) Damped Vibrations and Built-Up Vibrations. The damped vibrations and the built-up vibrations used in the tests are shown in Table 1. The vibration level was set at 40 VGL_p (a value formed by converting VAL_p into a VGL value). In the table, the Q value under damped vibration shows the changes in Q in the tank circuit (RLC) to vary the pulse wave-form. The time constant under built-up vibration shows changes in the time constant when integrating the short waves in order to vary the pulse wave-form.

TABLE 1. FREQUENCIES AND DIFFERENCES OF WAVE FORMS OF THE DAMPED AND THE BUILT-UP VIBRATIONS, AND THEIR EQUIVALENT DURATIONS

Their wave forms were modified by change of Q value in the tank circuit or of time constant in the integrating circuit.

(i) Damped vibrations

Frequency (Hz)	Decay process	Q value	Equivalent duration (sec) Whole body & hand, vertical & horizontal
15	Entry 1	46.6	0.067
	2	7.75	0.067
27	1	4.71	0.037
	2	2.47	0.037

(ii) Built-up vibrations

Frequency (Hz)	Wave form	Time of constant of integrating circuit (sec)	Equivalent duration (sec) Whole body & hand, vertical & horizontal
20	Entry 1	0.25	0.1
40	1	0.25	0.075
	2	0.10	0.025
60	1	0.25	0.067
	2	0.10	0.0167

Initially, a subjective comparison was made between the damped and built- /38
up vibrations and variable pulse period pulsed sinusoidal vibration at the same fundamental frequencies and the same p-p values to determine the equivalent pulsed sinusoidal vibration pulse period. The results are shown in the right hand column of Table 1. Specifically, the decay process in damped vibration was varied between two types (Entry 1 and 2), but it was discovered that, irrespective of the decay process, there was sensory equivalence to a one-period pulsed sinusoidal vibration with the same p-p value. It was also determined that the built-up vibration has a pulse period within 1.5 dB of its maximum

amplitude and is equivalent to a pulsed sinusoidal vibration having the same fundamental frequency and the same maximum p-p value.

It was given that the equal pulse period was the maximum histogram value when the equal sensation points were derived for damped and built-up vibration for the 10 subjects when pulsed sinusoidal vibration was varied every half cycle.

TABLE 2. COMPARISON BETWEEN THE OBSERVED (Obs) AND THE CALCULATED VGL_j VALUES (Cal) FOR THE DAMPED AND THE BUILT-UP VIBRATIONS

The calculated values were obtained by the equivalent duration in Table 1 and Eq. (2). Conversion of the VAL value into the VGL value can be made by Figures 6 and 9 in Report No. 1. Standard deviation of the observed values is ±1.5 dB.

(i) Damped vibrations

Freq. (Hz)	Decay process	Whole body vertical		Whole body horizontal		Hand vertical	
		Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
15	Entry 1	29.7	29.7	28.8	29.7	29.6	29.7
	2	29.2	29.7	28.8	29.7	28.8	29.7
27	1	28.6	28.0	28.7	28.0	29.5	28.0
	2	28.4	28.0	28.5	28.0	28.0	28.0

(ii) Built-up vibrations

Freq. (Hz)	Wave form	Whole body vertical		Whole body horizontal		Hand vertical	
		Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
20	Entry 1	31.5	30.9	31.0	30.9	31.3	30.9
40	1	29.8	30.0	29.5	30.0	30.5	30.0
	2	26.8	26.7	26.5	26.7	26.0	26.7
60	1	29.5	29.7	30.0	29.7	29.0	29.7
	2	26.5	25.6	25.5	25.6	26.3	25.6

If the above results are used, t in Eq. (1) is determined. In these pulsed vibrations, VGL_j can be calculated from the following since VGL_p is 40.

$$VGL_j = VGL_p - 7 \log_{10} \frac{T_o}{t} \tag{2}$$

On the other hand, the VGL values were determined when damped vibration and built-up vibration were directly equal sensationally to continuous sinusoidal vibration at the same fundamental frequency. The results were entered in Table 2 under the Obs. column for comparison with the calculated values. The standard deviation for the observed values for the 10 subjects was ± 1.5 dB. Both are in good agreement, falling within ± 1.5 dB. The suitability of Table 1 can be apprehended from this fact.

The above results, however, can only be applied when there is no marked variation between the fundamental frequency of the three types of pulsed vibration during the pulse period. For example, the above results cannot be used for such pulse waves as are produced when 20 Hz built-up half-waves and 5 Hz damping waves are supplied. They also cannot be applied to short single pulses.

4. Conclusions

The following evaluation method is derived from the above results.

(a) Pulsed Sinusoidal Vibration. Determined from the following if the acceleration level (dB) and (VAL_p) of a continuous sinusoidal vibration with the same peak value, the fundamental frequency (Hz) and the pulse period (duration) (seconds) are known.

$$VAL_j = VAL_p - 7 \log \frac{T_o}{t}$$

Where $T_o = 2$ seconds at $2 \sim 60$ Hz, $T_o = 0.8$ seconds at $60 \sim 200$ Hz and $T_o = 0.5$ seconds above 200 Hz. If this VAL value is converted into a VGL value in accordance with Figures 6 and 9, Report No. 1, the magnitude of the sensation can be determined.

(b) Damped Vibration. Is equal to pulsed sinusoidal vibration with a single period having a value equal to the maximum p-p value and it does not depend on the damping process.

(c) Built-Up Vibration. Is equivalent to pulsed sinusoidal vibration having the same fundamental frequency and a value equal to its maximum p-p value. The pulse period of this pulsed sinusoidal vibration is within 1.5 dB of the maximum value in built-up vibration.

(d) Damped Vibration and Built-Up Vibration. Based on paragraphs (b) and (c) these become an equivalent pulsed sinusoidal vibration. If the correlation in (a) is used, it is possible to obtain the sensory value VGL_j for pulsed vibration.

It is deduced that the correlation between the magnitude of pulsed vibrations as determined here and discomfort and tolerance limits can be determined from the matters discussed in Report No. 1.

In conclusion, thanks are extended to Professor Juichi Isoran (Tokyo University Aerospace Research Institute) and to Professor Hirono Sakabe (this Research Institute) for their guidance throughout the course of this study. Thanks are also extended to the researchers in this Institute who acted as subjects.

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